Passive wick fluxmeters: Design considerations and field applications

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[1] Optimization of water use in agriculture and quantification of percolation from landfills and watersheds require reliable estimates of vadose zone water fluxes. Current technology is limited primarily to lysimeters, which directly measure water flux but are expensive and may in some way disrupt flow, causing errors in the measured drainage. We report on design considerations and field tests of an alternative approach, passive wick fluxmeters, which use a control tube to minimize convergent or divergent flow. Design calculations with a quasi-three-dimensional model illustrate how convergence and divergence can be minimized for a range of soil and climatic conditions under steady state and transient fluxes using control tubes of varying heights. There exists a critical recharge rate for a given wick length, where the fluxmeter collection efficiency is 100% regardless of the height of the control tube. Otherwise, convergent or divergent flow will occur, especially when the control tube height is small. While divergence is eliminated in coarse soils using control tubes, it is reduced but not eliminated in finer soils, particularly for fluxes <100 mm/a. Passive wick fluxmeters were tested in soils ranging from nonvegetated semiarid settings in the United States to grasslands in Germany and rain-fed crops in New Zealand and the South Pacific. Where side-by-side comparisons of drainage were made between passive wick fluxmeters and conventional lysimeters in the United States and Germany, agreement was very good. In semiarid settings, drainage was found to depend upon precipitation distribution, surface soil, topographic relief, and the type and amount of vegetation. In Washington State, United States, soil texture dominated all factors controlling drainage from test landfill covers. As expected, drainage was greatest (>60% annual precipitation) from gravel surfaces and least (no drainage) from silt loam soils. In Oregon and New Mexico, United States, and in New Zealand, drainage showed substantial spatial variability. The New Mexico tests were located in semiarid canyon bottom terraces, with flash flood prone locations having extremely high drainage/precipitation ratios. In the wettest environments, drainage was found to be closely linked to the rate and duration of precipitation events.

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1. Introduction

[2] It is difficult to measure vadose zone water flow rates for at least three reasons. First, vadose zone flow rates span over 4 orders of magnitude, from less than 1 mm/a to more than 10,000 mm/a; second, spatial distribution of water fluxes are often highly variable over short distances making the measurements scale variant and often hard to interpret; and third, the placement of water flux sensors can disrupt the flow, causing either convergent or divergent flow with resultant inaccuracies in water flux estimates. At present, there is no standard method available for measuring soil water flux.

[3] Estimates of water flux are best derived from direct measurements. The most basic approach is the use of lysimetry [*Allen et al.*, 1991], where a quantity of drainage water is captured in a buried container, and in some fashion, drainage volumes are measured over time. A wide range of lysimeters has been employed, including pan lysimeters, equilibrium tension lysimeters and wick lysimeters, each with their own advantages and disadvantages.

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[4] Pan lysimeters collect only free drainage water and are sometimes called "zero tension" lysimeters, while tension lysimeters and wick lysimeters collect water under tension, either through a vacuum control system or applied via a hanging water column (i.e., wick). Pan lysimeters [*Richards*, 1950; *Jemison and Fox*, 1992; *Chiu and Shackelford*, 2000; *Zhu et al.*, 2002] are the least expensive system and have been used extensively over the years to assess drainage water quality and to a lesser extent to estimate water flux. Their major drawback is divergence, due to the fact that unless the soil is very coarse, or the pan is very large and the flow correspondingly high, flow around the pan can be significant, resulting in large underestimates of flow.

[5] The "equilibrium tension" lysimeter was originally conceived over 72 years ago by *Ivie and Richards* [1937], further developed by others [*Cary*, 1968; *Dirksen*, 1974; *van Grinsven et al.*, 1988, *Brye et al.*, 1999, 2001; *Barzegar et al.*, 2004; *Kosugi and Katsuyama*, 2004] and recently automated by *Masarik et al.* [2004]. The basic feature of the equilibrium tension lysimeter is the collection of drainage water from a buried pressure plate or membrane using vacuum, controlled at soil water tensions close to those found in the surrounding soil. This method is likely the most accurate water flux method but it is also the most expensive and most difficult to operate and maintain. Concerns about the reliability of tension control when near saturation [*Gee*, 2005; *Morari*, 2006] and possible effects of plate resistance on measured fluxes [*Kasteel et al.*, 2007] as well as interactions due to meter placement in the soil profile [*Mertens et al.*, 2005] add uncertainties to flux measurements when using the equilibrium tension lysimeter method.

[6] As a water flux meter, the passive wick lysimeter is a compromise between the complications and expense of equilibrium tension lysimeters and the simplicity of the less accurate pan lysimeter. Passive wick lysimeters maintain tension on the soil using an inert wicking material, such as fiberglass [*Holder et al.*, 1991] or rock wool [*Ben-Gal and Shani*, 2002]. A hanging water column is created, and drainage water is pulled out of the lysimeter while the lower soil boundary is "passively" maintained at a pressure less than atmospheric, so that the soil at the bottom of the lysimeter stays unsaturated. The degree of unsaturation depends upon the length of the wick and its hydraulic properties, the water flux, and the soil type [*Holder et al.*, 1991; *Boll et al.*, 1992; *Knutson and Selker*, 1994; *Rimmer et al.*, 1995; *Zhu et al.*, 2002]. For typical wick-type fluxmeters, the wick material is highly conductive and the wick area sufficiently large that flow in and through the lysimeter is not restricted. No external controller is used to maintain pressure; rather the lysimeter relies on the nearly static pressure created by the hanging water column (wick). The pressure in a wick lysimeter is always less (more negative) than that found in a pan lysimeter. Where direct comparisons have been made, passive wick lysimeters have generally outperformed pan lysimeters in their ability to capture drainage water [*Zhu et al.*, 2002] though not always [*Boll et al.*, 1997]. In extensive field testing, collection efficiency (CE) has been shown to equal or exceed 100% for passive wick lysimeters [*Louie et al.*, 2000] while average CE values for pan lysimeters were found to be less than half that amount [*Zhu et al.*, 2002]. Adaptation of the passive wick lysimeter concept has been made by *Gee et al.* [2002, 2003] who designed and laboratory tested what we call here a passive wick fluxmeter. In this design, drainage flux is measured automatically with a tipping spoon that collects water draining from a fiberglass wick. The wick "passively" controls the pressure head in the soil at a value that can approach the length of the wick. A soil-filled control tube is placed directly above the wick to minimize divergent or convergent flow. The major disadvantage of the passive wick fluxmeter is the lack of precision control of the tension, relying on the wick and control tube to approximate the range of tensions which dominate when drainage occurs, thus limiting the wick units generally to coarser-textured soils. The advantage of the passive wick unit over the vacuum controlled lysimeter is robustness and reliability for long-term measurements.

[7] In this paper, we investigate the use of passive wick fluxmeters as drainage monitors for a number of soil types and flux conditions. Specifically, we evaluate their performance for sand, loamy sand, structured clay, and silt loam soils, for fluxes from 1 to 10,000 mm/a, through modeling and then evaluate their field performance over a range of soils and climatic conditions. This paper reports a collection of studies, each with specific objectives, as described later. The overall objective was to assess the use of passive wick fluxmeters as reliable drainage monitors. The field study discussions highlight the broad range of conditions where fluxmeters can be applied.

2. Materials and Methods

2.1. Fluxmeter Design

[8] An objective in our design has been to make the passive wick fluxmeter robust enough to operate for multiple years without repair, recalibration or replacement. In the following, we describe passive wick fluxmeters that were specifically designed for long-term (multiple-year) use and at the same time were relatively easy to construct and install.

[9] The passive wick fluxmeter monitors drainage from a soil-filled funnel. The soil captures flow from a predetermined area where it drains into the funnel neck occupied by a conductive material capable of applying a capillary pressure to the overlying soil. Water flux is measured directly by placing a water monitoring device (e.g., miniature tipping bucket or recording autosiphon) below the lower end of the wick (Figure 1).

[10] The funnel neck is 2.5 cm in diameter and is filled with a fiberglass wick material that creates a hanging water column. In some of our tests (Figure 2, right), we used two intertwined fiberglass ropes (Pepperell Braiding Company, Pepperell, Massachusetts), each having a diameter of 12.7 mm. In other tests (Figure 2, middle), we used larger diameter (2.5 cm) wick material (Amatex, Norristown, Pennsylvania). The ropes were kiln dried at 400°C for 3 h to remove glue and other organic materials, as recommended by *Knutson et al.* [1993]. The top 15 cm of the wick material was separated into single strands, which were used to line the interior of the funnel. To prevent soil from filtering through the funnel and the wick, a thin layer of diatomaceous earth was placed in the bottom of the funnel

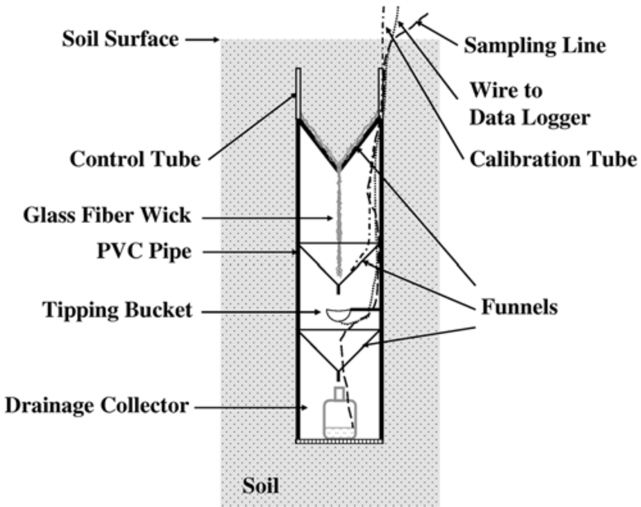

Figure 1. Schematic of a passive wick fluxmeter [after *Gee et al.*, 2002].

above the wick. Diatomaceous earth material is highly conductive and does not restrict flow within the fluxmeter. The wick extended vertically below the soil-filled funnel. Passive wick fluxmeters incorporate a method to control convergence or divergence of flow. The control tube consists of a plastic or galvanized pipe, about the same diameter as the top end of the funnel and extends from the funnel top up to a height of 60 cm. For the tests reported here, the inside diameter of the control tube ranged from 20 to 21 cm with corresponding surface area ranging from 314 cm^2 and 340 cm^2. Note that larger dimensions for wick and control tube can be accommodated in the design and have been used by others [*Jabro et al.*, 2008]. The K_{sat} of the wick is extremely high and under normal flow conditions (<10,000 mm/a) offers little resistance to the overall flow in the water fluxmeter.

[11] Water was collected from the wick in two ways. The first used a miniature rain gauge (Rain-O-Matic, Pronamic Co. Ltd., Silkeborg, Denmark) that consists of a reed switch and a small plastic spoon to which a magnet is attached (Figure 2, right). The tipping spoon is positioned in a 10.2 cm diameter. PVC plastic tube designed to isolate the wick from the surrounding soil. As the spoon fills and

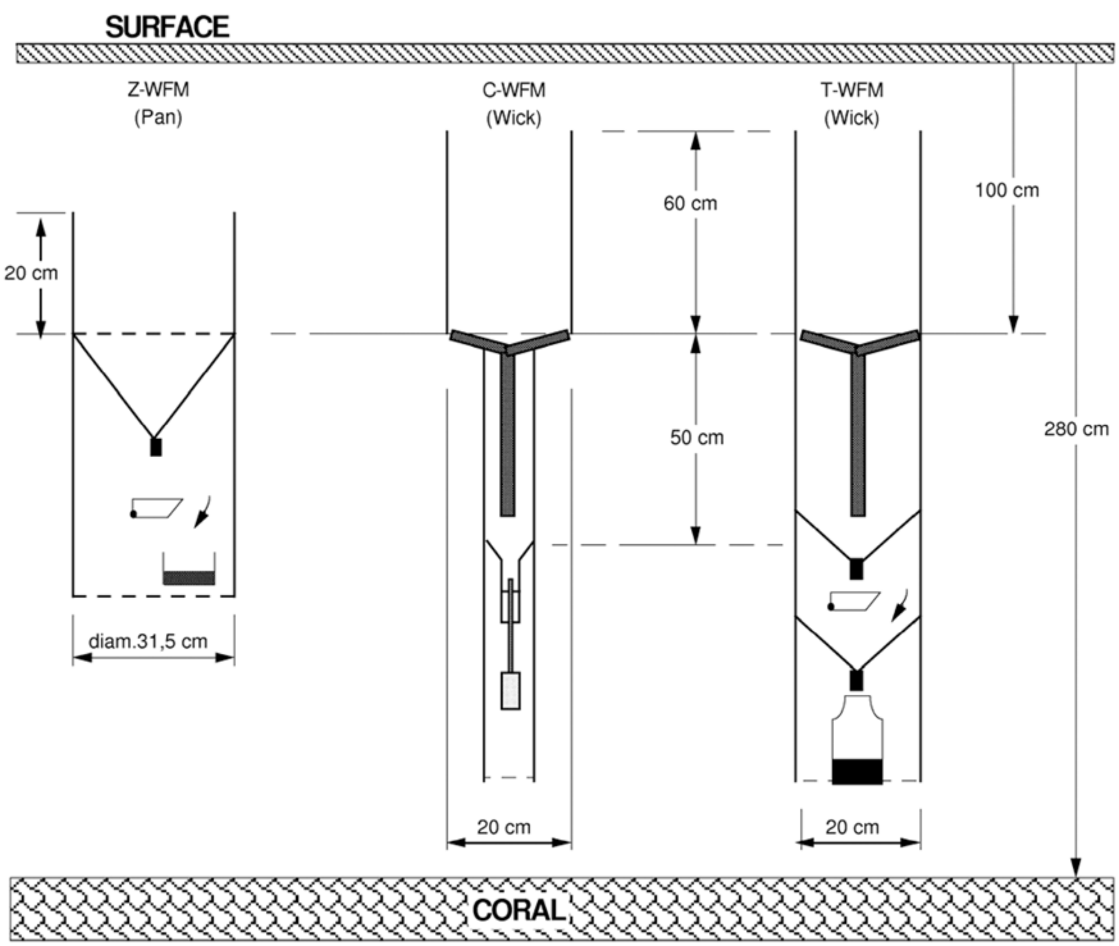

Figure 2. Schematic of three water fluxmeters tested in the same field in Tongatapu, Tonga. Shown from left to right are a pan-type (Z-WFM) fluxmeter, passive wick fluxmeter with-capacitance sensor (C-WFM), and passive wick fluxmeter with tipping bucket (T-WFM) [after *van der Velde et al.*, 2005]. Cups shown at the bottom of each fluxmeter represent the collection zones for water samples. The Gee wick unit uses a tipping spoon, while the Decagon unit uses an autosiphon and capacitance probe detector.

empties, the magnet moves past the reed switch, causing an electrical pulse to be counted on an event recorder. Because the tipping spoon is enclosed, there is no evaporation from it, and even when the soil drains and dries, the humidity near the tipping spoon typically remains at ~100%. All exposed components of the buried gauge are potted and sealed so that they do not corrode in the high humidity [*Gee et al.*, 2002]. A number of these tipping spoon units have been in the ground and operational now for over 6 years. For our fluxmeter design, a water flow rate of 0.6 mL/min (about 8 min per tip) was near the upper range of interest (i.e., ~10,000 mm/a). The lower range of interest is less than 1 mm/a, which is achievable because the resolution of one tip is equivalent to ~0.15 mm water. The second collection method (Figure 2, middle) uses an ECHO-type capacitance probe (Decagon Devices, Pullman, Washington) in a manner similar to that reported by *Masarik et al.* [2004] with the following modifications. The capacitance probe is placed in the center of a water reservoir (~60 mL capacity) and as the water fills the reservoir, corresponding electrical capacitance changes are recorded. As the capacity of the water collection chamber is approached, an autosiphon discharges the reservoir (~40 mL), and the process is repeated. Data loggers can be programmed to capture either the discharge or the stage as indicted by the changing electrical capacitance reading of the probe [*van der Velde et al.*, 2005]. Passive wick fluxmeters also have two other useful design features. The first feature is a sample tube that extends from the reservoir at the bottom of the meter to above ground. By inserting a syringe at the end of the sample tube, water samples can be extracted for analysis of leachate chemistry (Figure 1). The second feature is that a similar tube can be used to check the water measurement device calibration in situ (Figure 1). This verification is accomplished by injecting a known volume of water into the tube which then flows directly to the measurement system (not through the wick). One can then compare the amount of water injected with the amount measured.

2.2. Numerical Simulations

[12] Because of the mismatch that can occur between the soil water pressures inside and outside of the fluxmeter, convergent or divergent flow can occur but may be minimized by properly selecting the height of the control tube or adjusting the length of the wick. There are obvious limitations in changing these parameters and in preliminary tests we found that a 60-wick length and 60-cm control tube (Figures 1 and 2) appeared to work reasonably well for relatively coarse soil conditions (e.g., gravels, sands, etc.) of interest in agricultural and waste management applications. We did observe convergent flow in a well-aggregated clay soil under tropical rainfall conditions [*van der Velde et al.*, 2005] and were curious to know what the optimal design might be for this somewhat extreme situation. We were also interested in knowing under what conditions passive wick fluxmeters will work in finer soils for a range of water fluxes. To assist in this assessment, we ran a series of numerical simulations for a series of soils and fluxmeter dimensions.

[13] Flow was simulated using the Subsurface Transport Over Multiple Phases (STOMP) simulator [*White and Oostrom*, 2006], which is designed to solve a variety of nonlinear, multiple-phase, multidimensional flow and transport problems for unsaturated porous media. A cylindrical coordinate system was used, and only one vertical slice of the cylinder was used in the simulations. Because the flow through a water flux meter is axisymmetric, the simulation was equivalent to a three-dimensional simulation. The simulation domain was subdivided into a grid with variable spacing steps (Δx and Δz). The minimum value of Δx was 1 mm, which was at two locations where the bottom of the funnel and the wall of the fluxmeter reside. The minimum value of Δz was 2 mm, which was where the funnel was located. The modeling domain was 1 m horizontally and 2 m vertically and was discretized into 104 × 128 nodes (Figure 3).

[14] Both steady state and transient simulations were carried out. For the steady state simulations, the upper boundary conditions were set as a constant flux of 1, 10, 100, 1000, and 10,000 mm/a. The lower boundary outside the fluxmeter was set as a unit gradient condition and inside the fluxmeter, at the bottom of the fluxmeter, was set as a constant head of −60 cm or 0 cm for the case without a wick. The control tube length was varied in the modeling from 0 to 100 cm. The wall of the fluxmeter was treated as being impermeable. The differences between steady state and transient simulations were that for the transient cases, the upper boundary conditions were set as variable flux. Simulations were carried out for soils with four different textures: sand, loamy sand, structured clay, and silt loam soil. The hydraulic parameters are summarized in Table 1.

2.3. Field Tests

[15] As part of an informal collaborative program to evaluate methods for water flux (drainage) monitoring, passive wick fluxmeters were tested over the past 6 years at a number of sites throughout the world. We report results from eight sites, each with differing soils and climate. These include semiarid sites near Richland, Washington; Lakeview, Oregon; and Los Alamos, New Mexico, United States, and at semihumid and humid sites, including a grassland site in Germany, a squash plantation on the island of Tongatapu, in Tonga (South Sea Islands), and a potato field and a pasture site in New Zealand. At two locations (Richland and Germany), direct comparisons were made between drainage from large lysimeters and fluxmeters. At two humid sites (Tonga and New Zealand), drainage was estimated from water balance considerations. At the remaining two sites (Lakeview and Los Alamos) we looked at the utility of the fluxmeters to quantify subsurface flow and drainage using multiple fluxmeters, placed in locations where flows were expected to be highly variable. Additional details for each site are provided in the section 3.

3. Results and Discussion

3.1. Modeling

[16] For the flux analysis, we calculated the flux recovery or collection efficiency (CE = J_m/J_a), expressed as a percentage of the measured flux, J_m, to the actual flux, J_a, where the actual flux is the applied water flux incident on the meter. Values of CE > 100% indicate convergence while values less than 100% indicate divergence. Using the STOMP simulator and the soil characteristics for the four soils tested, we calculated the CE for passive wick flux-

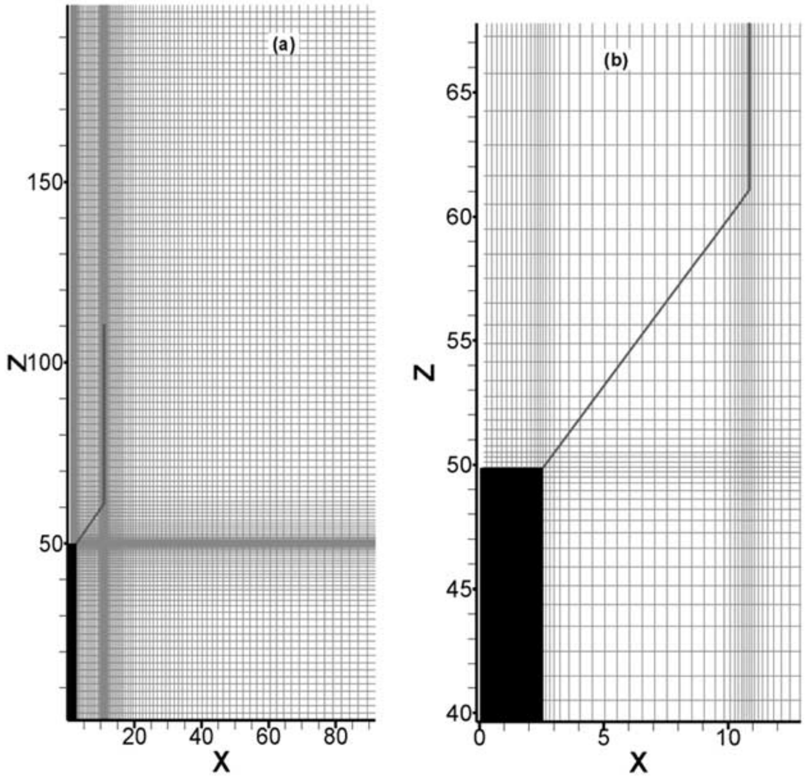

Figure 3. (a) Grid for STOMP simulations of passive wick fluxmeter with a 60-cm wick and a 60-cm control tube height. (b) Blowup of Figure 3a. The model assumes that the soil inside the fluxmeter is the same as the soil outside the fluxmeter.

meters that have varying control tube heights (from zero to 100 cm). The calculated CEs as a function of control tube height are shown in Figure 4 for the four soil types. There exists a critical recharge rate, q_c, under which the soil water suction equals the length of the wick (60 cm for our cases). Particular q_c values were 0.08, 935, 149, and 6644 mm/a for the sand, loamy sand, structured clay, and silt loam, respectively. If $q = q_c$, the CE was 100% regardless of height of the control tube. Otherwise, convergent (for $q > q_c$) or divergent (for $q < q_c$) flow was predicted, especially when the control tube height was too small. The use of a control tube will reduce the magnitude of both convergence and divergence errors. In all cases, the collection efficiency approaches 100% when the control tube height becomes very large. For a given soil with an annual average suction h (under a certain recharge rate, q), the sum of wick length, L_w, and the control tube height, L_c, must be much larger than h, i.e., $L_w + L_c \gg h$. Otherwise, no or very little drainage will occur. For example, for the loamy sand soil under a 100 mm/a recharge condition, the corresponding soil suction, h = 101 cm. Hence, $L_w + L_c \gg 101$ cm so that significant amount of drainage can occur. Unfortunately, there does not exist a critical value of $L_w + L_c$ such that the collection efficiency will be 100%. On the basis of the simulation results when using a 60-cm-long wick and under a 100 mm/a recharge condition, extending the control tube height to 80 cm ($L_w + L_c - h = 40$ cm) results in an CE value of ~80%. For many applications agreement between measured and actual drainage within 20% may be satisfactory.

[17] For coarse soil (e.g., sand, Figure 4a) passive wick fluxmeters with 60-cm-long wicks operate satisfactorily over the range from 1 to 10,000 mm/a. As soils become finer (Figures 4b and 4c), passive wick fluxmeters become less effective at low fluxes, but begin to perform satisfactorily at higher fluxes (>100 mm/a). In the silt loam soil (Figure 4d), divergence is still evident at fluxes >1000 mm/a. The impact of soil aggregation or macropores is evident in Figure 4c (structured clay), where collection efficiencies are higher than those found in loamy sand (Figure 4b) for devices having similar control tube heights. This result illustrates how both soil texture and structure help determine the range over which the fluxmeter is most effective. Where abundant macropores are present in soils, it is expected that CEs will be higher than where macropores are less abundant or absent.

[18] Transient inputs had less effect on flux efficiencies of passive wick fluxmeters than expected. We simulated transient inputs on the structured clay soil (Table 2). Cases were

Table 1. Soil Hydraulic Properties[a]

Soil	K_s (m s^{-1})	α (m^{-1})	N	θ_s (m^3 m^{-3})	θ_r (m^3 m^{-3})
Sand	2.92×10^{-4}	8.05	4.81	0.31	0.093
Loamy sand	2.00×10^{-5}	5.00	2.00	0.44	0.03
Structured clay	1.97×10^{-6}	5.00	1.49	0.59	0.49
Silt loam	1.00×10^{-5}	1.78	1.34	0.50	0.00

[a]Properties are for *van Genuchten* [1980]–type parameterization. Data for the sand, loamy sand, and silt loam soils taken from properties used for Hanford soils [*Gee et al.*, 2004]. Structure clay soil properties are for structured clay soil at the Tonga site [*van der Velde et al.*, 2005].

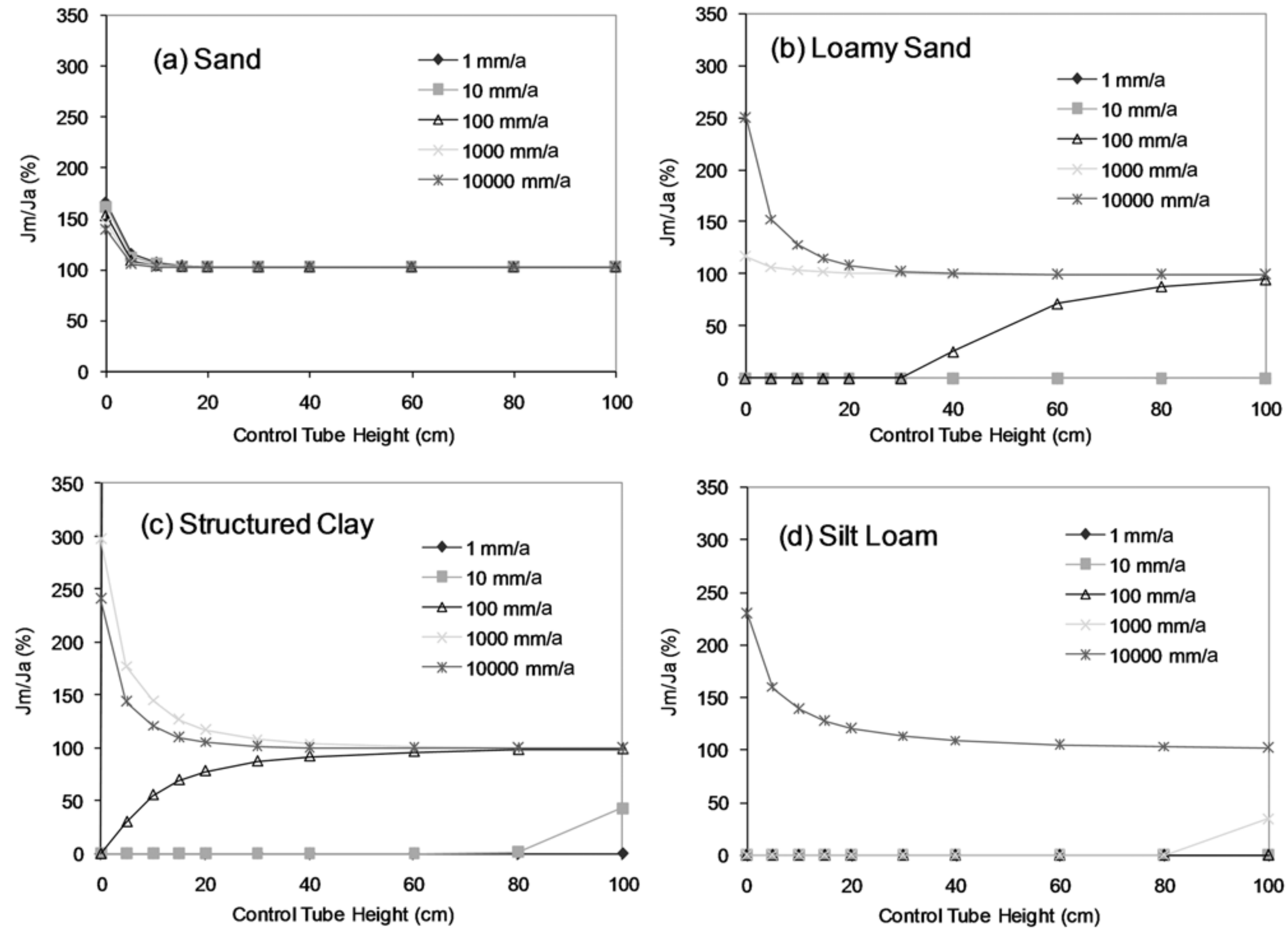

Figure 4. Simulated collection efficiency as a percentage (J_m/J_a = 100X measured/actual) for selected soils under a variety of steady flux conditions and control tube heights. These results are for passive wick fluxmeters with 60-cm-long wicks. When flux rates were 0.08, 935, 149, and 6644 mm/a for the sand, loamy sand, structured clay, and silt loam, the collection efficiency was 100% regardless of the control tube height.

run for fluxmeters with 60-cm-long wicks and with control tube heights of 0, 20, and 60 cm. Case TR1 applied water as follows: 12 events over 60 days, with rain occurring on every fifth day (i.e., on every fifth day it rained 17.5 mm, then no rain until the next fifth day). The rain was spread evenly over each rain day. Case TR2 applied four moderate rain events (22.5 mm/d every 12th day, i.e., on days 12, 24, 48 and 60), plus an extreme, 120 mm/d event on day 36. Differences in collection efficiencies between steady state and transient cases for the passive wick fluxmeter are relatively small, with differences varying from 5 to 15% over all test cases (Table 2). The effect of control tube height on drainage was far more dramatic. Without a control tube (H = 0), the CE value of the fluxmeter was excessive, with convergence causing as much as a threefold (300%) error in the measured drainage. In contrast, with a 60-cm control tube, the CE value was just over 100%, resulting in an error of less than 10% in the measured drainage for both the steady state and transient cases. In effect, the control tube offsets the impact of excessive wick length, particularly under conditions of relatively high water influxes (e.g., 1278 mm/a). This is an important design consideration and suggests that a passive wick fluxmeter with a sufficiently long control tube behaves much like an ''infinitely long column,'' making the wick length less important in affecting the pressure at the top of the fluxmeter, thus minimizing convergence or divergence. In our case, for the modeled soil (structured clay) and climate (210 mm infiltration in 60 days), the 60-cm-long control tube is not quite long enough to prevent some convergence. However, in terms of practical design it appears to be well within a reasonable error limit (<10%), and most of the field applications described later used a 60-cm-long control tube. These model results are comparable to those of *Gooijer* [2007], who simulated drainage from five soils types ranging from coarse sands to loams and reported that under steady state conditions coarse sands showed much less divergence than loam-textured soils. Our modeling results also agree with observations from laboratory tests, where fine soils show appreciable divergence and low collection efficiencies [*Kohl and Carlson*, 1997; *Gee et al.*, 2002]. The modeling conducted to date is not exhaustive. It is limited to just a few soil types and only one wick type with one fluxmeter area (340 cm^2) with varying control tube heights. However, the modeling does illustrate the general performance of this kind of passive wick fluxmeter and how divergence and

Table 2. Simulated Water Flow Inside and Outside a Passive Wick Fluxmeter and the Resultant Collection Efficiencies for a 60-cm Wick and Control Tube Heights[a]

Case	H = 0 cm	H = 20 cm	H = 60 cm
Cumulative Flux Outside of Fluxmeter (mm)			
SS 3.5 mm/d	210.1	210.1	210.1
TR-1, 12 events	210.5	210.5	210.5
TR-2, 5 events	209.8	209.8	209.8
Cumulative Flux Inside of Fluxmeter (mm)			
SS 3.5 mm/d	633.4	247.5	214.2
TR-1, 12 events	659.8	258.2	224.3
TR-2, 5 events	563.9	239.4	216.1
Collection Efficiency (%)			
SS 3.5 mm/d	301.5	117.8	101.9
TR-1, 12 events	313.4	122.7	106.5
TR-2, 5 events	268.8	114.1	103.0

[a]Control heights, H, are 0, 20, and 60 cm. Results are for steady state (SS = 3.5 mm/d) and for two transient cases (TR-1, 12 events and TR-2, 5 events) run for 60 days with a total of 210 mm applied for all cases.

convergence can be minimized. With further effort, nomograms of expected collection efficiencies could be developed for all combinations of soils and drainage rates of interest. Such an approach could lead to custom designing fluxmeters for site specific soil and climatic conditions. However, practical limitations of device size (length, area, etc.) and cost will most likely dictate an optimal design for a specific site. In future modeling, a more accurate method will require using actual dimensions and hydraulic properties of the wick and not assume a control of −60 cm at the bottom soil boundary. The present modeling assumes an ideal wick with no flow restrictions, hence the divergence (and convergence) we have estimated lies somewhere between that for an ideal wick and that expected for a pan lysimeter.

[19] *Mertens et al.* [2007] have used modeling to optimize the design of conventional passive wick samplers [e.g., *Brandi-Dohrn et al.*, 1996] for year-round assessment of drainage and chemical fluxes. *Mertens et al.* [2007] concluded that a wick with optimal hydraulic properties, but with a variable length, would minimize drainage errors by better matching the expected soil water pressure conditions, which vary with season at a proposed test site. However, their model did not include any assessment of control tubes to minimize the effect of seasonal pressure changes on drainage rates. Although aware of control tube technology, *Morari* [2006] and *Mertens et al.* [2007] expressed concerns that there might be preferential flow along the walls of the control tube which would compromise drainage estimates. While this may be a concern under saturated flow conditions, preferential flow along the walls of the control tube is normally restricted, if not eliminated, when the soil remains unsaturated and the top of the control tube is below ground surface. In our simulations, we assumed unsaturated flow occurred in all cases, so the impact of wall flow was not modeled explicitly.

[20] Another problem that can occur under ponded conditions is that they can give rise to perched water tables, particularly where subsoils are much less permeable than surface soils and rapid drainage is impeded. In fact, the issue of elevated water tables (ponding) in early spring is common at some locations and must be dealt with if year-round operation of fluxmeters is desired. Preferred sites for fluxmeter placement are those with permanently deep water tables (i.e., water tables that never rise above the bottom of the lysimeter or fluxmeter). In our design, this suggests that water tables should remain at least 1.2 m below ground surface. Other issues, such as soil disturbance during fluxmeter placement (leading to modification of hydraulic properties because of changes in texture, bulk density, layer sequences, etc.) and changes in natural preferential flow paths, including the impacts of biotic intrusion, such as roots, worms, ants, small animals, etc., should be recognized and addressed for each site. For cropped soils, surface land disturbance is a frequent practice, so fluxmeter placement via auger hole (or similar access) using disturbed soil in the control tube should not seriously compromise the fluxmeter performance, particularly for coarser-textured soils in agricultural settings. Similarly, fluxmeters with disturbed soil columns placed in engineered soils of landfill covers should also be acceptable because the land surface has already been highly disturbed. In some cases, fluxmeters may be built directly into a landfill cover (i.e., placed during construction of the landfill cover). Some complications may be encountered in areas with minimally disturbed landscapes and watersheds, but these are areas where localized drainage rates are generally of less interest than for agricultural lands or waste disposal sites. *Mertens et al.* [2005, 2007] and *Morari* [2006] have used modeling to show that placement and spacing of fluxmeters in the soil can give rise to measurement errors. Ensuring year-round performance of fluxmeters can present some challenges. For one thing, the pressure in the soil water typically changes with season. For nonirrigated or deficit irrigated cropland, summer typically produces lower (more negative) soil pressures and the fluxes are correspondingly low, making only a minor contribution to the annual drainage. It is when the soil wets up in the spring that it is most important for the fluxmeter to perform accurately to capture the bulk of the ''first-drainage'' events. For a silt loam soil, *Morari* [2006] has shown that errors of more than 30% occurred under high drainage conditions, when the pressures were not properly matched inside and outside the lysimeter.

[21] While optimal designs of passive wick fluxmeters are not finalized, the simulations reported here provide general guidance for using our fluxmeter design (e.g., 60-cm wick length, 60-cm control tube height, with a 300 to 340 cm^2 cross-sectional area). The modeling suggests that if soils are coarse textured (i.e., gravels, sands, structured clay, etc.), then our design should be a suitable tool for measuring drainage over the entire range of climatic conditions, from arid to humid sites. For finer soils, drainage monitoring with the passive wick fluxmeter is more restrictive and will most likely work best under irrigated conditions where large (>100 mm/a) drainage rates are anticipated. With this guidance in mind, we next provide field results that show just how well passive wick fluxmeters have performed in time over a range of soil and climate conditions.

3.2. Field Results

[22] The field study discussions below provide comparisons between fluxmeter results and other measures of

Table 3. Drainage Data Related to Surface Soil and Climate Obtained From Passive Wick Lysimeters From Six Locations[a]

Location	Surface Soil	Precipitation, mm	Water Fluxmeter, mm	Actual Drainage, mm
Hanford site location 1	sand	420	270	275
Hanford site location 2	gravel	450	180	190
Hanford site location 3	silt loam	450	0	0
Germany (grass meadow)	sand	1280	250	240
Lakeview, Oregon, United States	silt loam	410	600–996	NA
Los Alamos, New Mexico, United States	loam/sand	914	0–4148	NA
New Zealand (potato crop)	gritty silt loam	1150	742	700[b]
New Zealand (pasture)	silt loam	1265	384	359[b]
Tonga (squash plantation)	clay (aggregate)	350	540	250[b]

[a]New Zealand and Tonga Site drainage data estimated by water balance; all other drainage data from large lysimeters. The Hanford site is in Washington, United States. NA means not available.

[b]Water balance estimate.

drainage that help demonstrate the performance of fluxmeters under a variety of conditions. In addition, they describe the kinds of problems that can be investigated with fluxmeters, and some of the important issues that need to be considered during experimental design. A summary of passive wick fluxmeter data for the eight field sites with a range of soils and climate is provided in Table 3.

3.2.1. Measurement Comparisons: Passive Wick Fluxmeters Versus Lysimeters or Water Balance Estimates

3.2.1.1. Washington State Site

[23] The objective of this study was to compare drainage measurements from passive wick fluxmeters with existing deep drainage lysimetry. This site is located in south central Washington State on the U.S. Department of Energy's Hanford Site, which has a semiarid climate (cool wet winters, hot dry summers) with an average annual precipitation of about 180 mm/a. Drainage data were collected from passive wick fluxmeters for multiple years at three locations at this site. At location 1, two passive wick fluxmeters of standard design (60 cm wick, 60 cm control tube) were installed in a 7.6-m-deep drainage lysimeter [*Gee et al.*, 2005] and monitored for a period of 4.4 years. During this time the coarse sand surface of the lysimeter was kept free of vegetation. The drainage response of the fluxmeters was largely in response to winter rain and snowmelt as nearly half (348 mm) of the total (786 mm) precipitation drained (Figure 5). At location 2, a fluxmeter was installed in barren gravelly sand adjacent to a 1.5 m deep lysimeter containing the same gravelly sand material and was monitored for 4.1 years. At location 3, a fluxmeter was installed in barren silt loam adjacent to a 1.5 m deep lysimeter with similar silt loam texture [*Fayer and Gee*, 2006] and was monitored for 4.2 years. In all three cases, the fluxmeters and lysimeters were kept vegetation free during the test period. Drainage from water fluxmeters were compared between shallow placement of water fluxmeters and deep drainage from lysimeters with corresponding treatments. Annual drainage rates for the two paired fluxmeters at location 1 were comparable, and agreed to within 15% of the drainage observed from the deep (7.6 m) lysimeter in which the fluxmeters were placed (Figure 5). Water pressure heads were found to range from −45 to −60 cm (as measured with tensiometers) throughout the drainage period. This was comparable to the length of the wicks in the fluxmeters. At locations 2 and 3 at Hanford, under identical climate, the drainage rates varied according to surface texture. As expected, coarse gravel yielded the largest drainage and silt loam yielded the least drainage (Table 3 and Figure 6). Coarse gravels drained more than half the annual precipitation, which typically resulted from winter rain and snow. In contrast, silt loam soil stored a larger fraction of the winter precipitation and subsequently reduced the winter drainage. Its is recognized that the nondraining conditions observed in both the fluxmeter and lysimeter at Hanford are likely to be biased low because of the zero-tension lower boundary condition in each device. These data better represent the performance of a capillary barrier (with silt loam soil over coarse sand or gravel, where the silt loam is 1.5 m deep for the silt loam soil and effectively 1.2 m deep for the fluxmeter). The data confirmed that drainage events are linked closely to surface soil texture and that passive wick fluxmeters can successfully measure multiyear drainage rates ranging from zero to >100 mm/a, in close agreement with values obtained from large lysimeters at the Hanford Site.

3.2.1.2. German Site

[24] The objective of this study was to compare passive wick lysimetry with data collected from large weighing lysimeters. This study site is located at a lysimeter complex in a small catchment area approximately 10 km south of Falkenberg, Germany. The soil has a sand texture and drains readily. Two passive wick fluxmeters of standard design were installed adjacent to a large weighing lysimeter (1.13 m diameter and 2 m deep [*Meissner et al.*, 2007]). Drainage data were collected for 26 months (2.2 years) and the results of the fluxmeters were compared to the lysimeter drainage for the same period (Table 3 and Figure 7). Precipitation during the test period was 1240 mm while drainage from this grass covered sand was about 250 mm. Agreement between the lysimeter and passive wick fluxmeters was within 5% (240 mm versus 250 mm). In addition to providing accurate measures of drainage, fluxmeters with long-term, maintenance-free performance are preferred over those that must be serviced frequently. Both at the Hanford and German sites, the passive wick units were easy to

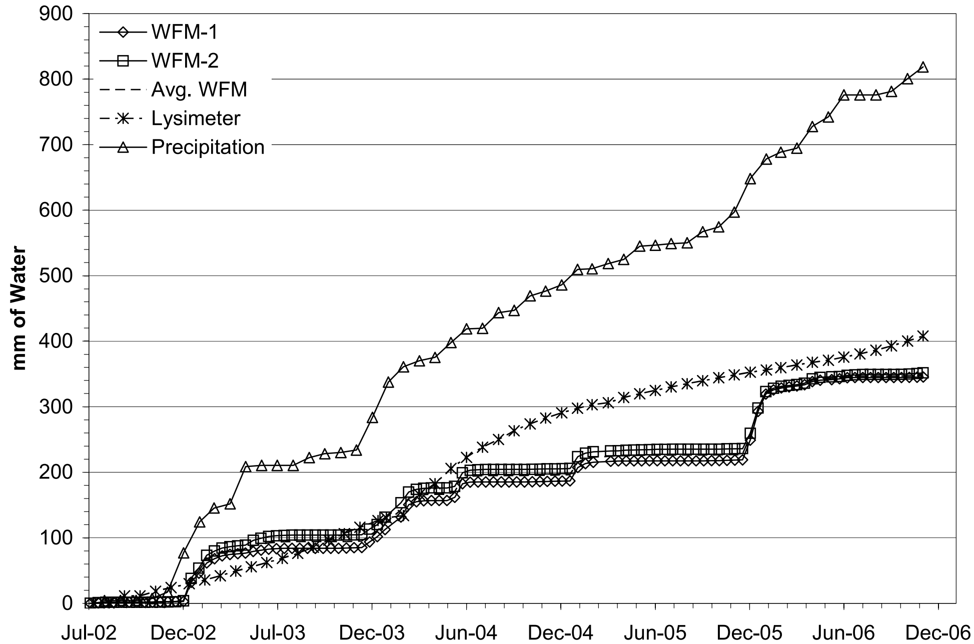

Figure 5. Hanford site location 1. Cumulative drainage from a bare sand surface by paired passive wick fluxmeters (WFM-1 and WFM-2) compared to measured precipitation (mm). Drainage occurs typically in winter months in response to rainfall and snowmelt events when evaporative demand is very low. Agreement between fluxmeter results for the 4.4-year test period is excellent. Fluxmeter drainage (360 mm) is nearly half of the cumulative precipitation and within 15% of that measured independently by the 7.6-m-deep lysimeter.

maintain and required little or no service during their operation.

3.2.1.3. Tonga Site

[25] The objective of this study was to compare drainage results from three different passive wick fluxmeters with drainage estimated from site water balance considerations. This study was conducted at a squash plantation on the island of Tongatapu in Tonga and is described in detail by *van der Velde et al.* [2005]. The soil is a structured, oxidized clay (volcanic ash) and is well drained. Three sets of fluxmeters (a total of six units) were installed at this site. Two sets were passive wick type, essentially the same

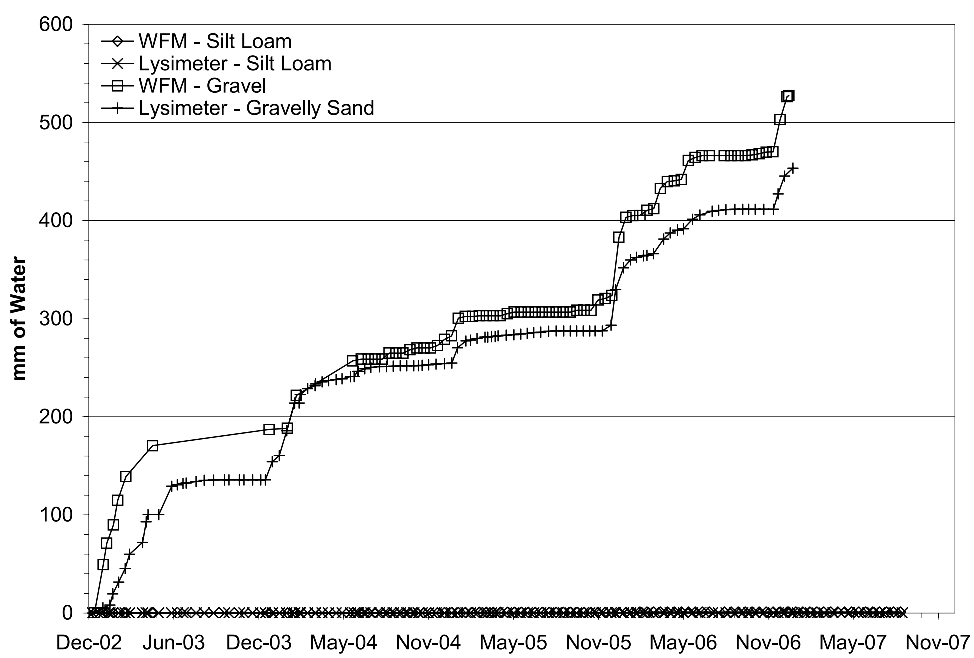

Figure 6. Drainage records from conventional lysimeters compared to passive wick fluxmeters for two soil types (gravelly sand and silt loam) at a semiarid site in Richland, Washington (United States).

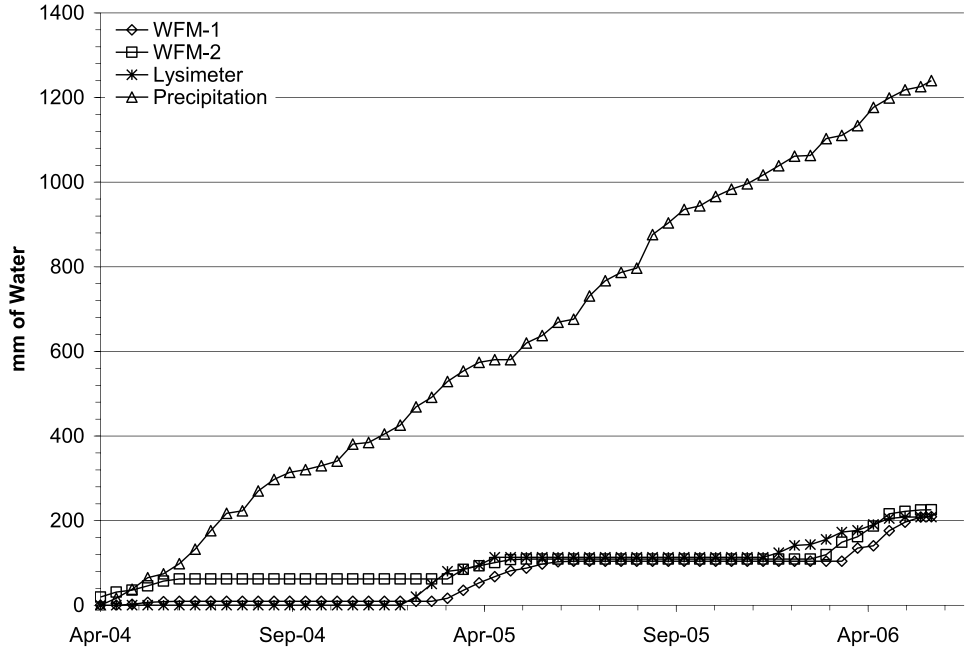

Figure 7. German site (grassland on a sandy soil) passive wick fluxmeters results compared to lysimeter results.

dimensions (60-cm control tube and 60-cm-long wicks) and one fluxmeter set was wickless, but with a 20-cm-long control tube (Figure 2). These units were installed in the soil in July 2003, immediately after the field had been ploughed and prepared for planting. Data were collected for a period of 60 days, during which rainfall totaled 340 mm. The site is relatively flat and no runoff was observed during the test. A simple water balance (i.e., drainage equals rainfall minus evapotranspiration) as described by *van der Velde et al.* [2006] was used to estimate drainage to be 217 mm. Drainage measured from the passive wick fluxmeters averaged 482 mm, yielding a collection efficiency of 223%. In comparison, the pair of wickless fluxmeters, each with a 20-cm-high control tube, collected an average of 240 mm drainage, yielding a collection efficiency of 110%. The high (>100%) collection efficiency from all fluxmeters is attributed to convergent flow. While the wickless units yielded drainage estimates close to that of the simple water balance, the passive wick units produced excessive drainage (collection efficiencies >200%). Soil water contents were measured during the tests but there were no direct measurements of soil water pressures or other hydraulic parameters (e.g., infiltration or field estimates of saturated hydraulic conductivity). The pressure conditions estimated by modeling with laboratory-determined hydraulic properties indicated that soil water pressure heads in the field could have been in the range of -10 to -20 cm (pressure head) during drainage events. It also should be pointed out that field-measured water contents were lower than those modeled by *van der Velde et al.* [2005], which suggests that actual field pressure heads could have been lower (more negative) than estimated from the simulations. This also implies that the actual drainage losses from the field may have been lower than estimated by the simple water balance calculations. However, the fact that drainage exceeded precipitation is compelling evidence that the passive wick units collected convergent flow during the 60-day test on this structured clay soil.

[26] Using STOMP, we simulated drainage from structured clay (Table 1) and found that for high drainage conditions (rates >1000 mm/a), collection efficiency should be $\sim$100% for a fluxmeter with a 20-cm-high control tube and no wick, in agreement with what was found in the field. Additional simulations also showed that for this soil, under high drainage conditions, wicks up to 20 cm in length with less than 20 cm high control tubes would work to minimize convergence errors. So it appears that the wick length of 60 cm used on our field test was not well matched to the soil and rainfall conditions. With hindsight, this mismatch might have been avoided if field measurements of the soil's hydraulic properties, and climate data had been used to premodel the site to determine the optimum device design (as suggested by *Mertens et al.* [2007]).

[27] It should be noted that our design model (Figure 2) using soil properties similar to those provided by *van der Velde et al.* [2005] showed that convergent flow could occur with passive wick fluxmeters, but not to the degree observed in the field. This could be the result of imperfect matching of the soil characteristics used in the model with actual field conditions. There is the possibility of localized ponding during heavy rains which could lead to excessive preferential flow not captured in the model. While we cannot rule this out, it seems unlikely that such phenomena would affect only the passive wick units and not the wickless units since they were all installed in the same pit and backfilled in a similar manner [*van der Velde et al.*, 2005]. On the other hand, there was some indirect evidence of local variations in water flow at the site. One of the passive wick fluxmeters quit working shortly after a heavy rain; then began working again as the soil drained, suggesting that there may have been temporary ponding around this fluxmeter. None of the other units experienced this problem. The tops of the passive wick units were located closer to the surface than the wickless fluxmeters (Figure 2), so the passive wick units were more accessible to near-surface ponding which could

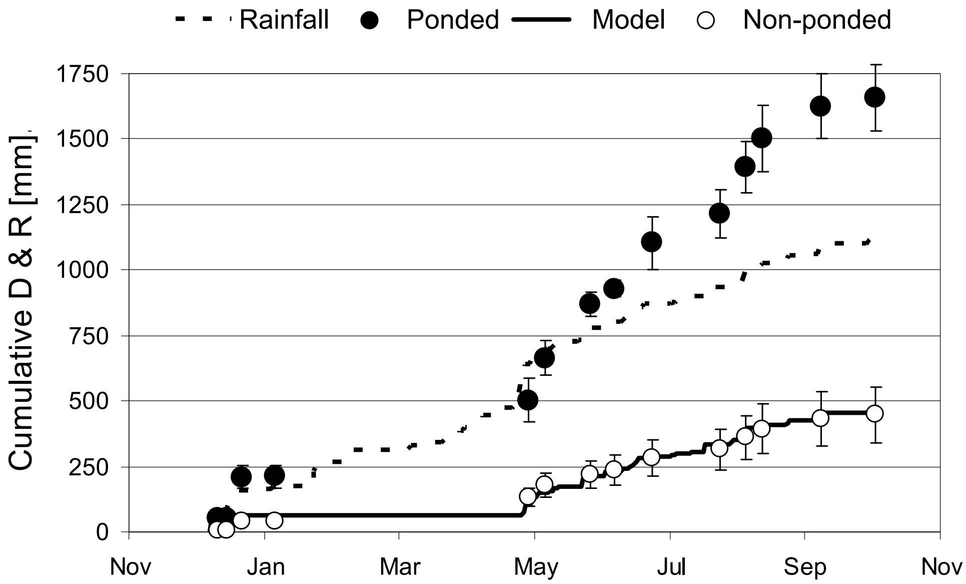

Figure 8. Water balance calculations of drainage losses from a potato field near Matamata, New Zealand (solid line). The open circles are measured drainage fluxes from nine passive wick fluxmeters that recorded less than the total rainfall. The solid circles are data from three other passive wick fluxmeters that recorded substantially more drainage than the total rainfall.

have occurred during intense rain storms. In a drainage study at a humid site (>2000 mm/a) in Sri Lanka, also with a well drained, structured clay soil, *Gee et al.* [2004] did not observe convergent flow using passive wick fluxmeters with the standard design (60-cm wick, 60-cm control tube). So generalizations about successful placement in structured clay soil cannot be made. From these Tongan tests it appears that for structured clay soils subject to high-flow rates that shorter wicks might have worked better than those used in the standard passive wick design. More site detail, such as field-measured pressure heads, and premodeling of the site, could help to better guide fluxmeter configurations in such soils.

3.2.1.4. New Zealand Site (Potato Field)

[28] The objective of this study was to evaluate the use of multiple passive wick fluxmeters for estimating the range of drainage from a New Zealand potato field. Fluxmeter results were compared to a simple water balance estimate. Six recording and six nonrecording passive wick fluxmeters were installed at a depth of 60 cm under a rain-fed potato crop near Matamata, New Zealand. The soil was a free draining Waihou gritty silt loam (typic orthic allophanic soil) with hydraulic and physical properties described in the New Zealand Soils Database (entry SB10113, Landcare Research, New Zealand). The fluxmeters were installed immediately after the crop was planted in November 2005. The soil surface was mounded into 30 cm high ridges at 90 cm spacings, and the passive wick fluxmeters were installed approximately halfway between the ridge and the furrow. During the first 2 weeks of the experiment there was enough rainfall, some 156 mm, to initiate drainage events through all of the passive wick fluxmeters (Figure 8). Thereafter, for the next 4 months cumulative evapotranspiration losses exceeded the total rainfall and so, as expected, the devices did not record any more drainage over the relatively dry summer period. Drainage recommenced in mid April 2006, coinciding with a die off of the crop canopy, and a rewetting of the soil profile following the early onset of autumnal rains. Drainage events were recorded often, throughout the winter period, usually following rainfall events > 5 mm/d. Over the 10 months of this experiment the fluxmeters drained about 65% of the total rainfall, on average (Table 3). However, there was a very wide scatter in measured drainage from the twelve passive wick fluxmeters (Table 4). Nine of the devices recorded less drainage than the total rainfall (we will refer to these as the "nonponded" set of passive wick fluxmeters). The other three devices recorded substantially more drainage than rainfall (we will refer to these as the "ponded" set of passive wick fluxmeters).

Table 4. Fluxmeter Results From the Potato Field Near Matatama, New Zealand

Fluxmeter[a]	Fluxmeter Drainage (mm)	Drain/Precip[b]
Auto-1	612	0.54
Auto-2	205	0.18
Auto-3	149	0.13
Auto-4	743	0.65
Auto-5	363	0.32
Auto-6	1501	1.31[2]
Man-1	155	0.14
Man-2	1097	0.96
Man-3	267	0.23
Man-4	1909	1.67[c]
Man-5	1568	1.37[c]
Man-6	427	0.37

[a]Auto refers to the six recording flux meters, and Man refers to the six nonrecording (manual) flux meters.

[b]Drain/Precip is the ratio of total drainage divided by total precipitation.

[c]Passive wick fluxmeters that were located in lower parts of the field where runoff and ponding most likely contributed to additional drainage volumes.

[29] The three ponded passive wick fluxmeters were located in lower parts of the potato field where runoff water and surface ponding was often observed following heavy rainfall events. This ponding most likely contributed to the additional drainage volumes recorded by these "ponded" devices. The tops of the control tubes were located at a depth of just 30 cm below the base of the furrows. Furthermore, the imprecise location of the passive wick fluxmeters in relation to the ridges and furrows, whose shape changed over the course of the growing season as the ploughed topsoil packed down, increases the likelihood that some of the passive wick fluxmeters would eventually be closer to the center of the furrow and therefore capture more percolation water that runs off the ridges. The converse is also likely, that some of the passive wick fluxmeters would measure lower drainage volumes if they were located closer to the tops of the ridges.

[30] If we average the drainage volumes from the nine "nonponded" passive wick fluxmeters then the measured drainage rates closely match model simulations of the site water balance that were performed using a simple water balance calculation [*Green et al.*, 1999]. The mean drainage of 446 mm was consistent with the estimated drainage of 456 mm obtained from the crop model calculator and overall water balance considerations. However, this may be fortuitous, because the coefficient of variation of the measured drainage rates from 12 lysimeters, over the whole growing season, was close to 80%. Averaging all twelve passive wick fluxmeters yielded about 60% more drainage than the model predicted.

[31] The performance of the passive wick fluxmeters in this well-drained New Zealand soil, was modeled by assuming the soil acts as a structured clay (Figure 4) and that the drainage rates were in the range from 100 to 1000 mm/a. Model output indicated that the standard design (60-cm wick and 60-cm control tube) would work for this site and should control both divergence and convergence. Care was taken to install all the fluxmeters in a consistent manner in the soil profile, so collection efficiencies should have been consistent among all units with the drainage variations reflecting the real variability in the field caused by microrelief and natural variability in soil transport properties. Unlike the Tongan test, the majority of the passive wick fluxmeters showed no evidence of convergent flow. Three fluxmeters did show excessive drainage but these results could be explained by observed localized ponding and topographic variations in the rows and furrows of the potato field. These results indicate that a larger number of lysimeters may be required to obtain a representative value for the average drainage losses under highly structured cropped soils.

[32] One would expect large variability in localized drainage rates in the case of cropped soils, where the field is ploughed and made ready for planting each year. In that case a hard pan may develop in some, but not all, places in the field. The experience with the NZ potato study is one example where additional variability in drainage would be expected because some furrows were observed to pond under heavy rainfall while others did not. This ponding leads to a redistribution of surface waters that eventually find their way into the soil, down the pathway of least resistance [*Deurer et al.*, 2003]. The New Zealand data clearly suggest that multiple measurements of drainage are required to capture the high variability that occurs in subsurface fluxes. *Zhu et al.* [2002] and *Morari* [2006], among others, have described a statistical procedure for assessing how many drainage meters might be required to obtain a preestablished level of accuracy (e.g., a 20% error margin). For the New Zealand potato field, it is apparent that more than 12 fluxmeters would be needed to achieve a 20% error margin. Practical limits in terms of initial cost and maintenance will preclude the installation of many more fluxmeters for any given test. The total number of passive wick fluxmeters will in part depend on how the data will be used. If spatial statistics were available for the site, optimization routines that place the meters at expected highest drainage locations might be employed, so that fewer meters could be used and yet allow the overall field-scale drainage to be assessed. Such an evaluation is yet to be completed at this site. There was a much smaller variation across the field in the nitrate concentrations of the drainage waters (leaching losses of nitrate will be reported elsewhere in relation to a nitrogen budget for this field crop).

3.2.1.5. New Zealand Site (Dry Land Pasture)

[33] The objective of this study was to evaluate the performance of multiple passive wick fluxmeters with undisturbed soil cores in assessing the range of expected drainage from a New Zealand dry-land pasture. Fluxmeter results were also compared to a simple water balance estimate. Twenty four recording passive wick fluxmeters were installed at a depth of 40 cm under a dry-land pasture on a flat site near Palmerston North, New Zealand. The soil was a poorly drained Tokomaru silt loam (argillic-fragic perch gley pallic soil) with hydraulic and physical properties described in the New Zealand Soils Database (entry SB09559, Landcare Research, New Zealand). The profile consisted of 20 cm of silt loam on 20 cm of silty clay loam with 20–40 cm of clay loam. The experimental site was part of a dairy farm and it was mole drained to a depth of 40 cm.

[34] For this experiment we used intact soil columns, with wicks shortened to just 10 cm to simulate drainage into the moles. Soil columns (20 cm diameter and 40 cm depth) were driven into ground that had been irrigated the previous evening using 20–30 mm of water. Each column was then excavated using a tractor-mounted back hoe, and placed immediately on top of a passive wick fluxmeter. A thin layer ($\sim$1 cm) of sand was used to establish good contact between the soil column and the fluxmeter device. The whole device was then placed into the ground such that the upper surface matched the surrounding pasture and the top 1–2 cm of the control tube extended above the soil surface to prevent runoff (or run on) of water. A weather station was located next to the fluxmeters to enable a calculation of potential ET from the pasture. TDR probes were also installed into the pasture, next to the passive wick fluxmeters, to record changes in soil water content from the top 0.4 m of the profile. The TDR probes and the weather station shared the same logger that also recorded drainage from the 24 passive wick fluxmeters.

[35] The flux meters were installed at the end of a very dry summer, and monitoring continued for the next 17 months (Figure 9). Over the course of the experiment the pasture received no irrigation and all stock was excluded from the site. The grass was mowed to a height of 3 cm, once every 1–2 weeks in the summer and less frequently over the

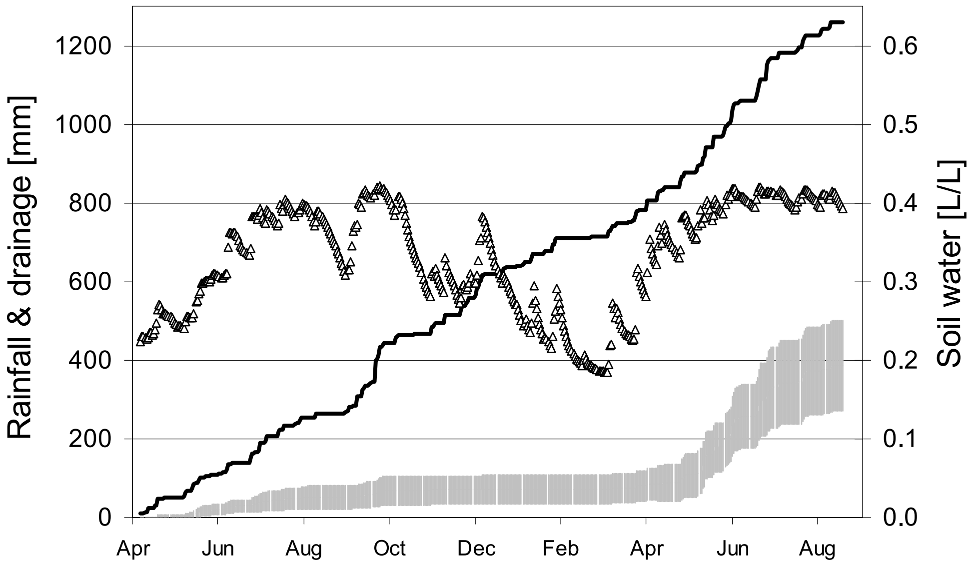

Figure 9. Time series of rainfall (black line), soil water content (open triangles), and drainage (gray line) under a dry-land pasture on a poorly drained Tokomaru silt loam near Palmerston North, New Zealand. Drainage data represent the mean and standard deviation of the cumulative drainage as measured from 16 passive wick fluxmeters.

winter. During the first winter (May to September) we recorded about 100 mm of drainage, on average, following some 400 mm of rainfall. The soil was initially quite dry (about 50% of field capacity) and it took about 3 months of winter rainfall before the soil reached field capacity. About 25% of the winter rainfall ended up as drainage. A large spring (September) rainfall in the first year helped to rewet the soil profile but it did not generate any significant drainage events. Similarly, a large rainfall event in mid summer (December) also did not yield any significant drainage. This was because the soil profile remained below field capacity (about 40% in the top 40 cm) on both occasions. More drainage occurred during the second winter (200 mm) because the soil remained wetter for a longer time because of more rainfall, and so a much larger fraction of rainfall (~85%) drained below a depth of 0.4 m. There was always a good correspondence between drainage events and times when the soil was close to or exceeded field capacity. We observed a moderate scatter (CV = ~30%) in cumulative drainage as recorded by 18 of the passive wick fluxmeters. Unfortunately, three of the devices failed to record automatically (possibly because of a programming error with the data logger) and another two devices failed halfway through the experiment because of problems with the tipping spoon mechanism. Nonetheless, all drainage water was collected by siphoning volumes out of the bottom of the passive wick fluxmeters devices, so that cumulative drainage losses were still able to be measured in each case.

[36] The performance of the passive wick fluxmeters in this poorly drained soil appears to be very good. Total rainfall (1265 mm) exceeded the pasture ET (906 mm) as calculated using the FAO-56 Penman-Monteith formula assuming a stress point of 30% (L/L) and a wilting point of 16% (L/L). Measured drainage rates (385 mm ± 116 mm standard deviation) were quite close to that expected from a simple water balance.

3.2.2. Additional Fluxmeter Studies Focusing on Spatial Variation of Drainage

3.2.2.1. Oregon Site

[37] The objective of this study was to determine if drainage was occurring through a shallow cover soil placed over uranium tailings. Three passive wick fluxmeters were installed in 2005 in the top slope of a landfill cover at a uranium mill tailings disposal site near Lakeview, Oregon (United States).

[38] The placement of the fluxmeters in the cover is shown in Figure 10. The tops of the fluxmeters are located in the tailings layer just below the clay layer that was intended to act as a radon gas barrier and a water drainage barrier. The passive wick fluxmeters began recording drainage in mid-November 2005, just 1 week after the start of a prolonged precipitation event, and continued to drain until early June 2006. Instantaneous drainage flux during this period ranged between 9,780 mm/a and 26,800 mm/a. Cumulative drainage values from the three fluxmeters are shown in Figure 11.

[39] The cumulative drainage was greater than total precipitation during the test period (Table 3). This is partly attributed to water harvesting, which occurs at this site as water that infiltrates the topsoil is diverted laterally downslope by gravity through an underlying coarse filter layer located just above the compacted clay layer. We measured the bulk density and moisture content of the clay layer as we excavated. The soil was then recompacted to match predisturbance conditions after placing the fluxmeters in the tailings. A falling-head technique was used to compare the saturated hydraulic conductivity (K_S) of the recompacted clay layer with undisturbed compacted soil nearby. The K_S values were comparable suggesting that the recompaction had negligible effect on hydraulic properties inside the fluxmeter (W. J. Waugh et al., Performance evaluation of the engineered cover at the Lakeview, Oregon, Uranium

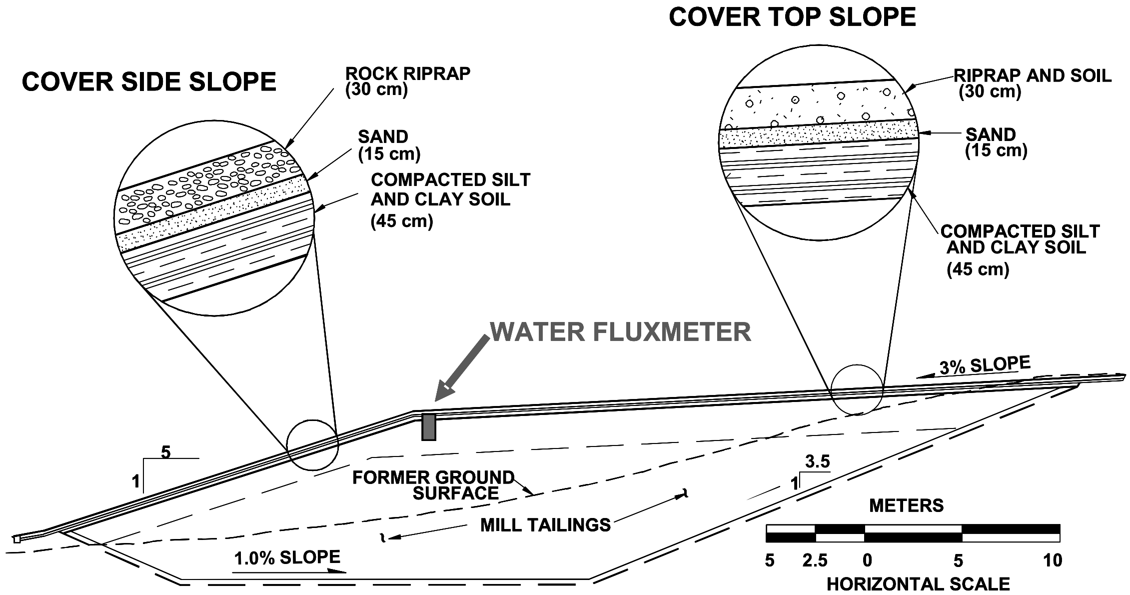

Figure 10. A cross section of the Lakeview site with an expanded view of the cover side slope and top slope. Fluxmeters were placed at the low end of the top slope and immediately below the compacted silt and clay layer shown in the expanded view.

Mill Tailings Site, paper presented at Waste Management 2007 Symposium, WMSymposia, Inc., Phoenix, Arizona).

[40] Snowmelt and rainfall in early spring produced significant lateral flow in the gravel drainage layer of the cover as it encountered lower-permeability clay liner causing the excess drainage water to move laterally downslope. Observations at this site indicated that sufficient water drained laterally across the top slope of the cover causing ponding of water and a high percolation flux at the low end of the top slope where the fluxmeters were located. Even though a high bulk density was achieved during construction of the radon barrier, root growth patterns and dye traces (observed during air entry permeameter tests) suggest that

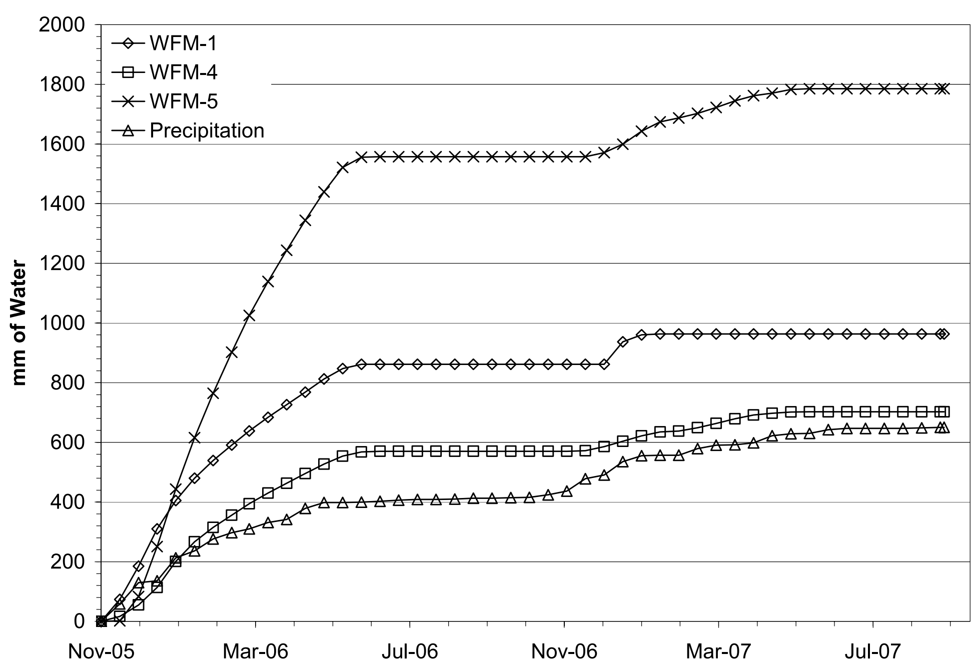

Figure 11. Cumulative precipitation and drainage from three passive wick fluxmeters at the Oregon site. The lower line is cumulative precipitation and the other three lines are fluxmeter drainage results. Drainage exceeds precipitation at all monitoring sites and is attributed to lateral flow of winter precipitation that infiltrates the landfill cover and then moves downslope over the clay liner.

preferential flow occurs through the clay layer (Waugh et al., presented paper, 2007).

[41] At all monitoring points, drainage was found to exceed the total precipitation. This suggests that in winter and early spring lateral flow is a prominent feature of the site water balance. Fluxmeters were helpful in determining that the landfill cover did not prevent drainage under these semiarid conditions.

3.2.2.2. Los Alamos Site

[42] The Los Alamos study was different to the other studies reported here in that the objective was to quantify transient drainage in a semiarid canyon floor with ephemeral flow. A specific objective was to examine the role of the terraces/floodplains in the canyon floor for generating deep drainage/potential recharge. Studies by *Constantz et al.* [2002, 2003], *Goodrich et al.* [2004], and others have shown that the channels in semiarid canyons and arroyos are locations where transient deep drainage events occur, and these locations can be important contributors to groundwater recharge. However, there has been little research on drainage in the terraces and floodplains adjacent to the stream channel under semiarid ephemeral flow conditions (see *Newman et al.* [2006] for a discussion of riparian zone drainage and lateral subsurface flow issues in semiarid drainages). The fluxmeter approach appeared to be a potentially useful way of monitoring transient drainage events, so a series of standard passive wick fluxmeters (with 60 cm wick and 60 cm control tube) was installed in middle to lower Mortandad canyon at Los Alamos National Laboratory, in north-central New Mexico, United States.

[43] Mortandad canyon contains nitrate, perchlorate, and radionuclide contaminated sediments and groundwaters as a result of former releases from activities at Los Alamos National Laboratory (see *Los Alamos National Laboratory* (*LANL*) [2006] for more specifics). Because contaminants reside within and below sediments on the canyon floor, it is important to understand how significant any transient drainage events might be. Twelve fluxmeters were installed at ten terrace locations along the canyon floor including on both sides of the channel and at two in-channel locations. This arrangement allowed us to evaluate spatial variability along approximately 3.2 km of the middle and lower canyon. The area spanned ponderosa pine forest (*Pinus ponderosa*) and piñon-juniper woodland (*Pinus edulis* and *Juniperus monosperma*) vegetation types and included a variety of topographic features.

[44] Fluxmeters were installed during late April through early May 2005 to monitor drainage from the upper 1 m of the canyon soils/sediments. The fluxmeters were installed in intercanopy spaces (outside of the drip line of any nearby trees). Some of the locations had thin (<30 cm) loam topsoils, but all the profiles were dominated by sand (often coarse sand). Given the sandy nature of the canyon sediments, the previously discussed problems with divergence should be relatively minor. During installation, the upper few centimeters of sod/topsoil was removed and carefully set aside so that it could be replaced over the fluxmeter in as intact a condition as possible. A power auger was then used to excavate a hole to sufficient depth for installation. The fluxmeters were lowered into the hole and the topsoil was then repacked on top of the fluxmeters in the same order as the in situ condition. Lifts were tamped every few cm to approximate the natural bulk density. The sands were not cohesive and typically had little horizonation, so the repack effect is expected to be relatively minor. Once the excavation was filled with soil to the appropriate depth, the sod/topsoil layer was replaced. There was approximately 20 cm of soil above the top of the divergence control tube. Little sign of disturbance (e.g., subsidence or dead vegetation) was evident at the surface during the ~2.5-year period after installation.

[45] The Mortandad canyon results are summarized in Table 3 and are reported in Table 5 for all twelve fluxmeters. The fluxmeter results indicated a transient nature of drainage in these types of environments. Even the fluxmeter with the most drainage (MCF9) frequently had many days with no drainage at all. Example plots from fluxmeters in different areas of the canyon floor are shown in Figure 12. There is a wide range of drainage values and drainage/precipitation ratios (Table 5).

[46] As noted earlier, the objective of the fluxmeter installations in Mortandad Canyon at Los Alamos was to examine the role of the terraces/floodplains in the canyon floor for generating deep drainage/potential recharge. The fluxmeter results clearly show that in most cases, deep drainage events (>1 m depth) do occur. Only one of the twelve fluxmeters (MCF2) did not register any drainage over the approximately 2.5-year period. In this case, evapotranspiration may be greater than the precipitation inputs creating upward fluxes that prevent deep drainage. MCF2 is located in the lower canyon where runoff events are not as frequent as the middle canyon locations [*LANL*, 2006].

[47] Drainage fluxes in the channel are typically higher and probably occur more frequently than most terrace locations. For example, fluxmeters MCF1 and MCF2 are adjacent to each other in the lower (and driest) piñon-juniper part of the canyon. MCF1, which is located in the channel, registered three small drainage events while MCF2, which is located on the north terrace, did not register any drainage. MCF7 is in a middle canyon channel location (ponderosa pine) and has the highest drainage of any fluxmeter except MCF9. Despite the importance of channels, generation of deep drainage and potential recharge from terraces in semiarid canyons and arroyos should not be dismissed because, as these results demonstrate, terraces can generate substantial deep drainage and typically occupy a much larger portion of the canyon floor than channels.

[48] Probably one of the most striking sets of results for Mortandad canyon are those from fluxmeters MCF6, MCF7, MCF9, and MCF10, all of which registered substantial amounts of drainage with drainage/precipitation ratios of 0.5 or higher (Table 5 and Figure 12). MCF7 and MCF9 even had drainage/precipitation ratios that exceeded 1.0. The MCF7 result is not surprising since it is in a channel location that has much more frequent flow events than MCF1 (the other channel location). The area where the terrace fluxmeters (i.e., MCF6, MCF9, and MCF10) were installed was subject to at least three events which flooded portions of the middle canyon. Most of these events were flash floods generated by summer storms. One event resulted from snowmelt following a large amount of snowfall (see the responses of MCF9 and MCF10 for February/March 2007 in Figure 12). The flood events can be seen quite clearly by the large jumps in cumulative

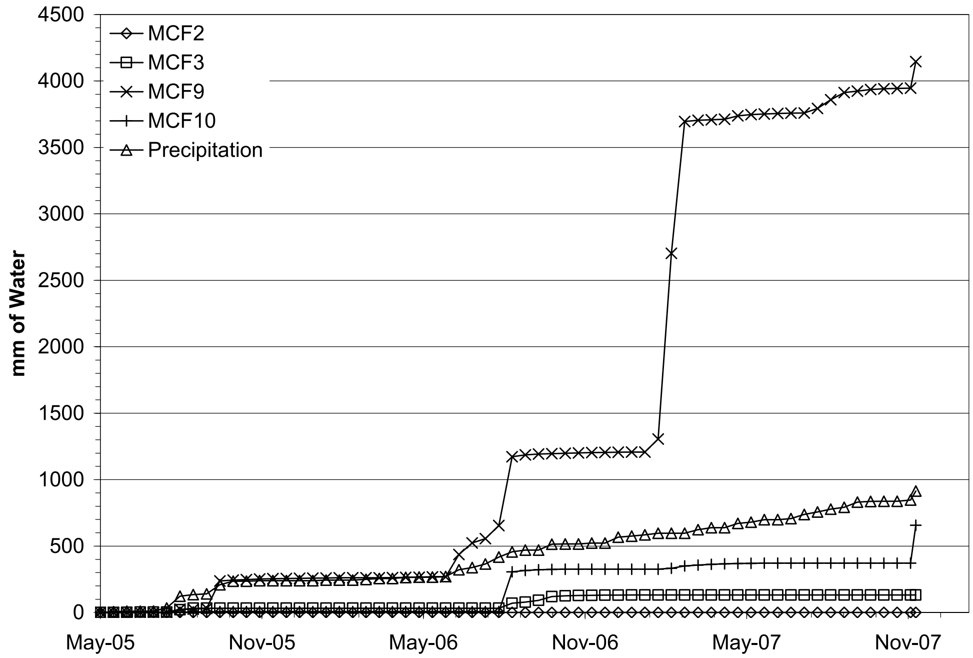

Figure 12. Cumulative drainage and precipitation from selected passive wick fluxmeters at the Los Alamos canyon site.

drainage in Figure 10. These results clearly show that floods from large and intense summer storms or snowmelt can be major drivers of substantial deep drainage in terrace/floodplain areas in semiarid canyons.

[49] Fluxmeters MCF4, MCF5, MCF8, and MCF11 were not subject to flooding and showed much lower drainage/precipitation ratios. On the other hand, MCF3 and MCF12 had intermediate drainage/precipitation ratios. These two fluxmeters were in low areas and the results reinforce the importance of topographic effects on drainage even at relatively small spatial scales. MCF3 was in a small depression in the lower canyon and had substantially more drainage than the next closest fluxmeter MCF5. MCF12 was installed in a sediment trap (installed to prevent contaminated sediments from migrating down canyon). Unfortunately, the flash flood in 2005 went over the top of the data logger and most of the results were lost. It is likely that drainage at this location was substantially higher than is reported here.

4. Conclusions

[50] The lysimeter studies in the United States at the Hanford site and in Germany at the Falkenberg site showed good agreement for paired fluxmeters tested against large lysimeters in coarse-textured soils. The lysimeter tests were run successfully for multiple years, suggesting that passive wick units are both accurate and durable for use in long-term studies with coarse-textured soils at these locations. Results from tests in Tonga and New Zealand show that in well-drained fine soils, convergent flow can occur but may be controlled by modifying the fluxmeter design (shorter control tube or shorter wick) to improve the collection efficiency of the meter. The New Zealand studies reveled moderate to large spatial variability that may be quantified

Table 5. Fluxmeter Results for Mortandad Canyon, Los Alamos, New Mexico

Fluxmeter	Surface Soil	Measurement Period	Precipitation (mm)	Fluxmeter Drainage (mm)	Drain/Precip[a]
MCF1[b]	Coarse sand	25 May 2005 to 3 Dec 2007	914.1	44.2	0.05
MCF2	Fine to coarse sand	13 May 2005 to 3 Dec 2007	914.1	0.0	0
MCF3	Coarse sand	13 May 2005 to 3 Dec 2007	914.1	131.3	0.14
MCF4	Fine to coarse sand	13 May 2005 to 1 Sep 2007	783.1	4.7	0.01
MCF5	Silty loam topsoil, coarse sand	13 May 2005 to 10 Nov 2007	837.1	1.2	0.001
MCF6	Silty loam topsoil, coarse sand	13 May 2005 to 11 Nov 2007	837.1	428.7	0.51
MCF7[b]	Fine to coarse sand	26 May 2005 to 4 Dec 2007	914.1	1799.9	2.0
MCF8	Fine to coarse sand	11 May 2005 to 14 Aug 2007	757.2	32.1	0.04
MCF9	Silty loam topsoil, coarse sand	11 May 2005 to 4 Dec 2007	914.1	4147.6	4.5
MCF10	Silty loam topsoil, coarse sand	11 May 2005 to 4 Dec 2007	914.1	658.1	0.72
MCF11	Silty loam topsoil, coarse sand	11 May 2005 to 4 Dec 2007	914.1	65.4	0.07
MCF12[c]	Silty loam topsoil, fine to coarse sand	13 May 2005 to 6 Dec 2007	914.1	258.3	0.28

[a]Drain/Precip is the ratio of total drainage divided by total precipitation.
[b]In-channel location.
[c]MCF12 drainage is likely underestimated; logger was damaged in flood.

by use of multiple passive wick flux meters. The New Zealand studies also showed that intact soil cores may be used successfully to estimate ranges of drainage from poorly drained soil. The results from the Oregon site show that both slope and soil type are important in documenting drainage flux. Lateral flow can dominate on sloping lands where subsurface soils are compacted and this can cause downslope areas to receive excess drainage waters. The results from the Mortandad canyon study at Los Alamos demonstrate that fluxmeters can be used effectively to understand the impacts of spatial variability on drainage particularly in terraced land and floodplains in a semiarid canyon with ephemeral flow. The relatively low cost of passive wick fluxmeters is an advantage in these kinds of studies where measurements in multiple areas are needed to properly capture spatial variability in drainage fluxes. Experimental results demonstrate that the canyon terraces do exhibit transient deep drainage, and only one out of twelve fluxmeters registered no drainage at all. Spatial variability in drainage was substantial and drainage/precipitation ratios ranged from 0 to 4.5. Floods were especially important in some areas for generating high drainage/precipitation ratios. Topographic depressions were also areas where local drainage was relatively high.

[51] Passive wick fluxmeters provide a simple and cost-effective way to quantify drainage where such data have been difficult to obtain in the past. Optimizing the performance of these devices depends on the soil type and the climatic conditions. The good agreement over multiple years, between drainage obtained with passive wick fluxmeters and drainage measured with adjacent large lysimeters, or estimated via simple water balances, is encouraging and supports the use of passive wick fluxmeters for long-term drainage studies, particularly in coarser soils. In finer textured soils, passive wick fluxmeters perform best under higher drainage fluxes (e.g., >100 mm/a). Fine soils tend to drain at lower pressure heads (more negative) than coarse soils, and this limits the operational range of wick lysimeters. In cases where there are fine soils that are highly aggregated or otherwise contain macropores, passive wick fluxmeters work much like they do in coarser (sandy) soils, but are subject to uncertainties that occur with preferential flow conditions that move ponded surface waters rapidly downward through root channels and worm holes, etc., giving rise to highly variable drainage. Multiple fluxmeters are needed in such cases to help capture and assess the degree of spatial variability. Rainfall intensity and duration must be considered in designing fluxmeters for humid sites where localized ponding may cause convergent flow resulting in an overestimate of drainage rates. Proper matching of wick length and control tube height to the soil pressure conditions expected during typical drainage events will improve the performance of the passive wick units, although standard configurations (e.g., 60-cm wicks and 60-cm control tubes) appear to work well for a number of applications, particularly in coarser-textured soils. An additional advantage of the passive wick fluxmeters described here is that drainage water can also be sampled for chemical characterization in a straightforward way [e.g., see *Gee et al.*, 2003]. Time series of coupled chemistry and drainage data collected from a single instrument makes passive wick fluxmeters useful tools for examining nutrient and contaminant transport problems. In addition, we are currently evaluating the suitability of fluxmeters for sampling stable isotopes (e.g., δ^2H and δ^{18}O), which would broaden the applicability of this type of instrumentation.

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